Surface water quality assessment with a fuzzy inference system

https://doi.org/10.56238/sevened2024.004-010

Edith Meryluz Claros-Guerrero[1] and Fredy Román Paredes Aguirre[2]

ABSTRACT

Freshwater is a water resource that has been deteriorating due to natural causes and anthropogenic activities, requiring the evaluation of water quality, comparing the values of physical, chemical and biological parameters with a Water Quality Index. In this study, the surface water quality of the Huaura River Basin (2019-2021) was evaluated, with a fuzzy inference system (FIS), based on the Environmental Quality Standards (ECA), and the categorization of water use according to the National Water Authority (ANA), category 3: Irrigation of vegetables and animal beverages. The theoretical underpinnings of the ICARHF fuzzy index were designed in four steps: define fuzzy sets and membership function; fuzzy set operations; fuzzy logic and inference rules. The Technical Reports of two surface water quality monitoring points in the Huaura River Basin (2019-2021) were analyzed. FIS logic (ICARHF) was implemented with Matlab R2022a. The fuzzy index is correlated with the Surface Water Resources Environmental Quality Index (ICARHS) (r=0.92), accepting that there is no statistically significant difference between the two indices. The results prove that it is possible to design a fuzzy inference system to determine surface water quality, depending on the use to which the water is intended, based on the information available from governmental and non-governmental entities, even when there is little accessible information.

Keywords: Water quality index, Fuzzy logic, Water resource.

[1] Universidad Nacional del Santa- Peru
Dr. in Mathematics
Docente at Fac. of Sciences/José Faustino Sánchez Carrión National University
ORCID: http://orkid.org/0000-0002-2765-953s
E-mail: eclaros@unjfsc.edu.pe
[2] José Faustino Sánchez Carrión National University
Teacher at Fac. of Chemical and Metallurgical Engineering
Master's Degree in Higher Education and University Research
ORCID: http://orkid.org/0000-0002-3829-9541
E-mail: fparedes@unjfsc.edu.pe

INTRODUCTION

Anthropogenic activities are negatively affecting water quality, considering that the term water quality is not directly related to an absolute or close to absolute degree of purity; it is closer to the concept of "natural" (Koch, Bianchi, Grutka, Martins, de Almeida, da Silva, da Rosa, & Alessi, 2023), these activities such as mining, cattle ranching, production and waste disposal, generate the presence of organic matter, through domestic wastewater discharges, agricultural runoff, industrial process effluents (Quiñones-Huatangari, Ochoa, Milla-Pino, Bazán, Gamarra, & Ráscon, 2020; Uddin, Nash, Rahman, & Olbert, 2023), and according to the report of the National Institute of Statistics and Informatics (INEI), the quality of water in Peru is being affected by the pollution of rivers, along their course, by the dumping of mining tailings, urban sewage and industrial drains (INEI, 2017), with harmful effects on health and the ecosystem, requiring water quality assessment, to maintain human health and protect the environment (Nayak, Patil & Patki, 2020), and this is determined by comparing physical, chemical and biological characteristics of a water sample with water quality guidelines or environmental quality standards (ECAs), to obtain water quality indices (AQIs) (ANA, 2018), to do this, mathematical equations are used, which qualify the body of water and provide a unique number that expresses the quality of the water (Yogendra & Puttaiah, 2008), allowing the assessment of water resource quality more easily in different locations, rather than comparing numerical values of several parameters (Nayak et al., 2020) of a water sample, the values of which will provide relevant information to promote efficient environmental management at local, regional and national levels.

The fuzzy logic approach has inherent advantages of "flexibility" and the ability to address "vagueness" and "uncertainty" more effectively. (Nayak et al., 2020), providing conditions for reasoning, inference, control, and decision-making in cases of uncertainty that allow real-world problems to be addressed (Zadeh, 1978; Sarkheil, Rahbari, & Azimi, 2021) , through the inclusion of a linguistic term that is easy for the population to understand, due to its ability to reflect human thoughts and experience in ICAs, which processes non-linear, uncertain, ambiguous and subjective information (McKone and Deshpande, 2005; Oladipo, Akinwumiju, Aboyeji, & Adelodun, 2021) whose success is based on the possibility of solving complex problems, difficult to solve using traditional methods (Martínez & Andrade, 2016), and simulates the human reasoning pattern in the design of the ICA (Oladipo et al., 2021).

This article is based on the results of the doctoral thesis: Evaluation of the surface water quality of the Huaura River Basin, Huaura district, with a diffuse inference system, based on pollutants, whose objective of the study is to evaluate the surface water quality of the Huaura River Basin with a fuzzy inference system taking as a reference the water-related environmental quality standards (ECAs-Water) and the use of to which the water of the Huaura River, in the District of Huaura, is destined.

MATERIALS AND METHODS

To meet the objective of the research, we proceeded to build an FIS, which allows to determine the quality of the water, from the observation of the facts and the generalization of rules of inference, such that it seeks to emulate the behavior of what is observed, in four steps: (1) Define the fuzzy sets and belonging function; (2) fuzzy set operations; (3) fuzzy logic; and (4) rules of inference (Uddin et al., 2021). The Technical Reports for Monitoring Surface Water Quality in the Huaura River Basin (2019-2021) were analyzed, from two monitoring points: Point 25 RHuau2: Huaura River, downstream of the CD Quipico Intake (571 meters above sea level) and Point 26 RHuau3: Huaura River, downstream of the Huaura Bridge (54 meters above sea level). The parameters were chosen according to the categorization of the National Water Authority (ANA), which establishes that the use of water from the Huaura River is classified in category 3: Irrigation of vegetables and animal beverages (MINAM., 2017), 12 parameters were considered, according to the ICARHS methodology (ANA, 2020): Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Thermotolerant Coliforms, Hydrogen Potential (pH), Arsenic (As), Cadmium (Cd), Manganese (Mn), Lead (Pb), Aluminum (Al), Iron (Fe) and Copper (Cu).

The process was carried out in two stages, in the first, it was sought to know the concentration of pollutants in the water, through the presence of parameters that exceed the values established in the RCT, the universe of discourse of each parameter was identified. The triangular membership function was selected for the normal or acceptable linguistic variable, when the RCT value of the selected parameter is unique, and trapezoidal if the RCT value is an interval; and for the linguistic variables Very Low, Low, High and Very High, measured from 0 (zero presence of contaminants), to 100 (Very high concentration), it is characterized with trapezoidal functions. The max operator that extracts the maximum degree of belonging of a parameter that exceeds the values of the ECA is used. The parameters were grouped into subsystems, respecting the characteristics and interaction in the water, the correlation of the parameters, following theoretical and statistical approaches (Uddin et al., 2021), in strict compliance with the regulations of the RCTs and the regulations in force in Peru (MINAM., 2017), with conditional inference rules IF – THEN, Mamdani type, for each subsystem.

In the second stage, the quality of the water was evaluated according to the presence of pollutant concentration, using fuzzy rules; To assess the quality of the water, the MIN operator is used, i.e. the lower the degree of contamination, the better the water quality, classified into five ranges, which are levels of sensitivity that express and qualify the state of the water quality, in:

Excellent (Very low, Low (min) or No contamination); Good (Very low (max), Low, Normal, or Acceptable (min)); Fair (Low (max), Normal or Acceptable (min)), High). Poor (Normal or Acceptable (max), High, Very high (min)) and Terrible (High (max) and Very high), with the discourse universe being from 0 to 100 (ANA, 2018, 2020). The FIS logic was built using the Fuzzy Logic Designer App, and the user interface was built using the App Designer, components of the Matlab R2022a software.

RESULTS AND DISCUSSION

For the theoretical support of the FIS, in stage 1, the fuzzy variable was identified:

values of the parameters obtained from the Water Monitoring; X:

Y: concentration of pollutants in water, generated by the presence of the substance (agent k), and the function of belonging to the substance.

$$y_k = \mu_{A_k}(x_k)$$

Where:

x_k = maximum value set in the RCT for the parameter k

A_k = fuzzy set of some parameter , as input set$k$

U_k = Parameter Speech Universe, $kU_k = [0, x_n]$;

When the RCT of a parameter has only one value, a triangular membership function is constructed for the linguistic variable: normal or acceptable, denoted by ; with; $kx_k \in U_k\mu_{A_k}(x_k) = 1$

When the RCT, for some parameter, has an interval, or more than one value, the trapezoidal membership function denoted by ; $k, I_k = [0, x_n] \subset U_k\mu_{A_k}(I_k) = 1$

Subsystems were generated that evaluate parameters with similar characteristics or consequences in water (), of the parameters: ; with Universe of discourse of the proportion of the pollutant generated by the presence of the parameters, of each subsystem ; $LnA_s = A_1 \cup A_2 \cup \ldots A_L L < n$; $U_j = 1, \ldots, Lj$m = acceptable ratio; ; , with the max operator, you get the output value for the rules for each subsystem .$U_j = [0{,}100]; m \in U_j\mu_{B_j}(m) = 1j$

In stage 2:

Y: represents the proportion of the concentration of pollutants in the water (input), resulting from stage 1 of the subsystems. j

Z the Water Quality Index, which defines the fuzzy set (output) that represents the quality of the water, affected by the set of parameters that are part of the subsystem; with the min. C j

Being Universe of discourse; with;; Referential value where the membership function of linguistic variables is normal. $U_j = U_j = [0{,}100]$; $a \in U_j \mu_{C_j}(a) = 1 a =$

Trapezoidal functions are considered for all linguistic variables: Excellent with an index of 95-100; Good with 80-94; Fair with 65-79; Bad at 45-64; and Abysmal 0-44 (Anna, 2020; Uddin et al., 2021).

The FIS mathematical model was then implemented through the Fuzzy Logic Designer App for the 12 selected parameters (ANA, 2018, 2020), in addition to two sub-indices: ICAMOF, Fuzzy Water Quality Index, based on parameters related to Organic Matter; ICAFQF, Fuzzy Water Quality Index and the ICARHF (Water Quality Index of the Huaura Fuzzy River).

For the ICAMOF, the subsystem 1:OD is considered with , which indicates the recovery capacity of the watercourse, and its absence causes anaerobic decomposition; COD measures the pollution of wastewater and effluents from domestic and industrial organic wastewater; BOD with , measures the amount of oxygen required by microorganisms (bacteria) to oxidize, degrade, or stabilize organic matter under aerobic conditions. Subsystem 2, with the parameter Thermotolerant coliforms, as a pollutant resulting from fecal contamination from untreated domestic discharges and animal waste that is incorporated into the receiving bodies. $U_1 = [0\ ,130]$ mg L^{-1} y $ECA =$ 15 mg $L^{-1} U_2 = [0\ ,250]$ mg L^{-1} y $ECA = 40$ mg $L^{-1}, U_3 = [0, 10]$ mg O2 L^{-1} y $ECA > 4$ ó > 5

For the ICAFQF, subsystem 3, which contains pH, is considered with ACE: or , which is the concentration of hydronium ions contained in a solution, if pH < 7 (acidic water) causes corrosivity; neutral water pH = 7 (ideal) and alkaline water pH >7, unpleasant taste, and causes changes in the fauna and flora of water bodies $U_4 = [0, 14]\ y\ 6.5 - 8.5\ 6.4 - 8.4$(Sierra Ramírez, 2011), sources of Mn ion contamination with ACE= and with , ACE= are produced from industrial wastewater (mining, pesticides, organic chemicals and others) and the reaction rate depends on the pH. $U_5 =$ $[0, 0.3]$ mg L^{-1} y 0.2 mg $L^{-1} Fe U_6 = [0, 8]$ mg L^{-1}5 mg L^{-1},

In subsystem4, As with 0.2 was included; with ACE= and Cd with ACE= As, a heavy, poisonous and highly toxic metal; Pb is a widely distributed element in low concentrations in sedimentary rocks and is toxic to aquatic organisms; Cd, a metal that is toxic to plants and animals, which are the product of industrial activities (mineral concentrator plants, poultry and others) and introduced into the environment through wastewater and the use of fertilizers. $U_7 =$ $[0, 0.30]$mg L^{-1} y $ECA = 0.1$ ó $Pb U_8 = [0, 0.1]$ mg L^{-1} y 0.05 $U_9 =$ $[0, 0.1]$ mg L^{-1}, 0.01 ó 0.05.

In subsystem5, Al con = and ECA= were considered to be of toxic relevance to plants (Pabón, Benítez, Sarria, & Gallo, 2020)$\boldsymbol{U_{10}}[\mathbf{0}, \mathbf{8}]$mg $L^{-1}\mathbf{5}$ mg L^{-1}, and Cu, and ACE= , since at higher levels, it generates toxic effects on plant growth.$\mathbf{U_{11}} = [\mathbf{0}, \mathbf{1}]$mg $L^{-1}\mathbf{0.2}$ ó0.05

The Mamdani conditional inference rules IF – THEN for each subsystem have the following syntax:

$\boldsymbol{R_1}$If the values of (BOD) is low and the values of (COD) are low and high values of (DO), then the proportion of pollutants in the river water is low. $\boldsymbol{x_1 x_2 x_3}$

In a similar way, the rules of inference are constructed for the 5 subsystems considered in this research.

In relation to the FIS output, 145 inference rules are constructed with the AND operator, as follows:

: If the proportion of the pollutant is very low and the proportion of is very low, and the proportion of is very low and the proportion of is very low, proportion of is very low then Water Quality Index is (excellent).$\boldsymbol{R_1 y_1 y_2 y_3 y_4 y_5 z_5}$

To validate the FIS, the values obtained from the monitoring (Table 1) of the water quality of the Huaura River of two monitoring points were used, according to the regulations in force in Peru, are in charge of the Local Water Authorities (ALA-Huaura), these points were selected, because they are located in the jurisdiction of the district of Huaura, scope of study of the thesis, and at the same time have a greater number of selected parameter values; since it is not always possible to take all the samples, due to the fact that it is conditioned to the dry season and flood according to the characteristics of the Basin, as can be observed in the Huaura River, in the month of October 2019, samples of thermotolerant coliforms were not taken, because the flow of the river was very low, and did not comply with the water quality monitoring protocol.

Table 1. Surface water quality monitoring results of the Huaura River -CD Quipico and Puente de Huaura:2019 – 2021

Date		**Physicochemical and biological parameters**											
		DBO	**DQO**	**OD**	**Coli**	**pH**	**Mn**	**Fe**	**Pb**	**As**	**Cd**	**Al**	**Cu**
		mg O2	--mg L^{-1}---		$ug\ L^{-1}$		------------------------------------mg L^{-1}-----------------------						
03 2019	RHuau 2	2	3	7.72	5400	6.85	0.21	5.74	0.000	0.008	0.0001	4.62	0.01
	RHuau 3	2	2	7.73	>40000	7.21	0.21	6.48	0	0.008	0.0001	5.50	0.01
10 2019	RHuau 2	3	27	5.93	0*	7.85	0.06	0.47	0.002	0.005	0.0001	0.30	0.02
	RHuau 3	3	32	4.91	0*	7.07	0.05	0.14	0.000	0.004	0.0001	0.07	0.00
06 2020	RHuau 2	2	16	7.32	4600	8.36	0.02	0.11	0.000	0.004	0.0001	0.18	0.00
	RHuau 3	9	42	8.39	>40000	7.76	0.02	0.19	0.002	0.003	0.0001	0.12	0.00
11 2020	RHuau 2	3	2	7.64	490	8.31	0.02	0.35	0.001	0.004	0.0001	0.29	0.00
	RHuau 3	10	37	2.26	40000	7.62	0.03	0.20	0.004	0.003	0.0001	0.15	0.00
05 2021	RHuau 2	2	16	7.68	33	8.49	0.03	0.27	0.001	0.004	0.0001	0.19	0.00

	RHuau 3	5	16	8.36	2800	7.77	0.02	0.12	0.000	0.003	0.0001	0.08	0.00

0* no sampling was performed for this parameter

The values obtained from the water quality monitoring were entered into the FIS interface, which was implemented in the Matlab software, using Mamdani-type conditional rules, and with a defuzzification method, the centroid, as a center of gravity, with triangular and trapezoidal membership functions coinciding with Quiñones-Huatangari et al. (2020) while Nayak et al. (2020) He believes that the defuzzification method of the bisector works best. In this study, the fuzzy indices were obtained: ICAMOF, ICAFQF and ICARHF, all independent in the calculation, since it does not require a historical record of data, and they are obtained in real time, and in the absence of the value of a parameter in the monitoring, the logic of the system assumes that the parameter is in the permissible range. which can be seen as an advantage, as it does not prevent the index from being obtained, however it could influence the final result.

For validation purposes of the fuzzy index, the result of the FIS is compared with the values obtained by the ICARHS index (ANA, 2020) whose methodology requires knowing the values of the total parameters to be evaluated (F1-Scope), amount of data that do not comply with the regulations requiring historical data, at least information from 4 monitorings (F2-Frequency), total surpluses that indicate the deviation of the data (monitoring results) from the standard (F3-Amplitude), to obtain Subindex 1 and Subscript 2, being the ICARHS, The lower value of both, i.e. the index depends on the values of the sub-indices and in the absence of either of the values, the calculation of the index is difficult.

In both methodologies, it is rated on a scale of 00-100, establishing five ranges: 95-100 Excellent (E); 80-94 Good (B); 65-79 Regular (R); 45-64 Bad (M); 0-44, lousy (P) (Table 2)

Table 2. ICARHS Vs ICARHF Index Values in CD Quipico and Puente de Huaura: 2019 – 2021.

Water Quality Monitoring		**ICARHS†**				**ICARHF‡**			
		S1	*S2*	Decision		ICAMOF	ICAFQF	Index	Decision
CD Quipico	2019	42.66 (P)	74 (R)	Lousy		32.74 (P)	81.25(B)	48.27	Lousy
	2020	99.2 (E)	81 (R)	Regular		83.28 (B)	88.76(B)	83.65	Well
	2021	89.4 (B)	99(E)	Well		96.37(E)	88.76(B)	88.76	Excellent
Huaura Bridge	2019	42.46 (P)	99 (E)	Lousy		32.74 (P)	70.24(R)	42.45	Lousy
	2020	42.44 (P)	99(E)	Lousy		31.31 (P)	88.76(B)	46.23	Lousy-Bad
	2021	42.68 (P)	99 (E)	Lousy		32.74 (P)	88.33(B)	43.76	Abysmal

Terrible (P); Bad(M); Regular (R); Good (B); Excellent (E); Sub-Index1 (S1) Water Quality Index - Organic Matter (ICARHS); Sub-Index2 (S2): Water Quality Index -Physical and Chemical Parameters: $ICARHS = \min(S_1, S_2)$

$$\dagger \; CCMEWQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right)$$

‡ Fuzzy Inference System (FIS), proposed in this research.

For the calculation of the ICARHS for the year 2019, monitoring information corresponding to the years 2017 and 2018 was used, since it is necessary for this methodology to have all the values of the parameters to be considered for the calculation of the index.

As can be seen in Table 1 and Table 2, there is contamination due to the presence of organic matter in the water of the Huaura River, especially downstream of the Huaura River bridge, since it is an area adjacent to the capital of the district, so the ICAMOF at both monitoring points is terrible; and in relation to the presence of metals, they do not exceed the ACE, which does not considerably influence the decrease in surface water quality.

When contrasting the results obtained by both methodologies, the substantial difference is that the ICARHS needs information on the frequencies (number of data, which the RCTs do not meet, on the total amount of data), while the FIS, evaluates the results for each monitoring without the need to know the frequency, uses the information of all the parameters and presents the result in real time. However, by not considering historical data as a reference, it could give erroneous information, for such a case, personalized analysis is used for each parameter, and this allows to know the percentage of affectation to the variation of an indicator, to identify the group of substances that are affecting the natural ecosystem, postulating itself as a computational tool, which allows identifying sampling points, with little information available, and depending on the use, to which the water is to be put.

Since fuzzy logic allows evaluation of subjective information, the results must be correlated to validate the results (Vergara & Gayso, 2008), and to determine if there is a statistical difference in the results of both methodologies, Pearson's correlation coefficient is obtained and with r=0.92, it represents a high and positive correlation, so it is accepted that there are no significant differences between the results of the ICARHS index and the diffuse ICARHF index, agreeing with what was obtained by Oliveira et al. (2014), who found a significant correlation between the results of the fuzzy index (IQABF) and the IQAB, while $R^2 = 91\%$ Quiñones-Huatangari et al. (2020) obtains , between the fuzzy index (DQWDI) and the values of the NSF WQI index. $R^2 = 0.81$

Therefore, FIS is an effective tool to address water quality issues (Quiñones-Huatangari et al., 2020) as it gathers expert knowledge and manages uncertainties by entering a range rather than a single value (Oladipo et al., 2021), on which water quality standards are generally based, in addition to the FIS, carries out the evaluation in real time, without the need for data, which, due to the economic cost of water analysis or the geographical complexity of the area, makes it difficult to obtain the information required to evaluate the quality of surface water.

CONCLUSIONS

If it is possible to design a fuzzy inference system of surface water quality, based on the information available from governmental and non-governmental entities regarding the monitoring of certain parameters of interest according to the objective of the institution, based on fuzzy inference rules, if... So..., so it is important to identify the universe of discourse of each parameter to be evaluated, based on the current regulations, the location of the area and the categorization of the use of the river water, which is going to be analyzed, and the opinion of the experts to adequately formulate the rules of inference and simulate their interaction, based on the user's requirements, in a friendly and simple way in real-time operation.

REFERENCES

1. ANA. (2018). Metodología para la determinación del índice de calidad de agua Ica-PE, aplicado a los cuerpos de agua continentales superficiales. Perú. Retrieved from https://hdl.handle.net/20.500.12543/2440

2. ANA. (2020). Índice de Calidad Ambiental de los Recursos Hídricos Superficiales (ICARHS). Perú. Retrieved from https://hdl.handle.net/20.500.12543/4479

3. INEI. (2017). Estadísticas Ambientales. (INFORME TÉCNICO N° 12 - Diciembre 2017). Retrieved from https://m.inei.gob.pe/biblioteca-virtual/boletines/estadisticas-ambientales/2017/1/#lista

4. Koch, S., Bianchi, V., Grutka, S. A., Martins, C. T. A., de Almeida Alves, A. A., da Silva, J. A. G., da Rosa, J. A., & Alessi, O. (2023). Diagnosis of Water Quality in an Urban Wetland. *Revista de Gestão Social e Ambiental*, 17(2), e03225-e03225. https://doi.org/10.24857/rgsa.v17n2-022

5. Martínez, R. N., & Andrade, S. H. H. (2016). Integración de la lógica difusa a la dinámica de sistemas para la selección de terrenos de cultivos agrícolas. *Elementos, 6*(6), 149-166. https://doi.org/10.15765/e.v6i6.842

6. Nayak, J. G., Patil, L., & Patki, V. K. (2020). Development of water quality index for Godavari River (India) based on fuzzy inference system. *Groundwater for Sustainable Development, 10*, 100350. https://doi.org/10.1016/j.gsd.2020.100350

7. Oladipo, J. O., Akinwumiju, A. S., Aboyeji, O. S., & Adelodun, A. A. (2021). Comparison between fuzzy logic and water quality index methods: A case of water quality assessment in Ikare community, Southwestern Nigeria. *Environmental Challenges, 3*, 100038. https://doi.org/10.1016/j.envc.2021.100038

8. Oliveira, M. D. d., Rezende, O. L. T. d., Oliveira, S. M. A. C., & Libânio, M. (2014). Nova abordagem do índice de qualidade de água bruta utilizando a lógica fuzzy. *Engenharia Sanitária e Ambiental, 19*, 361-372. https://doi.org/10.1590/S1413-41522014019000000803

9. Pabón, S., Benítez, R., Sarria, R., & Gallo, J. (2020). Contaminación del agua por metales pesados, métodos de análisis y tecnologías de remoción. Una revisión. *Entre Ciencia e Ingeniería, 14*(27), 9-18. https://doi.org/10.31908/19098367.1734

10. Quiñones-Huatangari, L., Ochoa, L., Milla-Pino, M., Bazán C, J., Gamarra T, O., & Rascón, J. (2020). Water quality index using fuzzy logic Utcubamba River, Peru. *Revista de Ciencias Agrícolas, 37*(1), 6-18. https://doaj.org/article/dadddef3eba4410db1e63a476d8cc8ef

11. Sarkheil, H., Rahbari, S., & Azimi, Y. (2021). Fuzzy-Mamdani environmental quality assessment of gas refinery chemical wastewater in the Pars special economic and energy zone. *Environmental Challenges, 3*, 100065. https://doi.org/10.1016/j.envc.2021.100065

12. Sierra Ramirez, C. A. (2011). Calidad del agua: evaluación y diagnóstico. *Ediciones de la U*.

13. Uddin, M. G., Nash, S., & Olbert, A. I. (2021). A review of water quality index models and their use for assessing surface water quality. *Ecological Indicators, 122*, 107218. https://doi.org/10.1016/j.ecolind.2020.107218

14. Vergara, G., & Gayoso, J. (2008). Una aplicación de métodos de conocimiento base y clasificación difusa para predecir calidad de agua en tres comunas del sur de Chile. *Bosque (Valdivia), 29*(2), 127-135. https://doi.org/10.4067/S0717-92002008000200005

15. Yogendra, K., & Puttaiah, E. (2008). Determination of water quality index and suitability of an urban waterbody in Shimoga Town, Karnataka. *Proceedings of Taal2007: The 12th world lake conference*.

16. Zadeh, L. A. (1978). Fuzzy sets as a basis for a theory of possibility. *Fuzzy sets and systems, 1*(1), 3-28. https://doi.org/10.1016/S0165-0114(99)80004-9